Calibration and validation of the SWAT model for hydrological simulation in a basin in Western Bahia

Hydrological modeling presents itself as a fundamental tool for the management and management of water resources, since it helps in understanding the streamflow, sediments and contaminants in a hydrographic basin. The Correntina River basin, located in the western region of Bahia, has been undergoing an intense process of alteration in its landscape motivated by the expansion of agricultural areas in the region, requiring the adoption of instruments for studies that assess the environmental impacts mainly on surface water resources. In view of this, the present study aimed to evaluate the effectiveness of the SWAT model for representing the hydrological behavior in the basin of the Correntina River, using the SWAT-CUP for automatic calibration and validation. Statistical performance coefficients attested the model's capacity for hydrological simulations in this basin on a monthly time scale, with KGE, Pbias, NSE and R^2 showing values of 0.69, 0.57, 0.5% and 0.74 in the calibration stage, and 0.73, -3.95 %, 0.64 and 0.76 in the validation step, respectively. In addition, the SWAT was also shown to be suitable for simulating the flow duration curves, characterizing the model as a good tool to aid the management of water resources in the basin under study. Subsequent studies will make it possible to analyze the impacts of land use and climate change on the hydrological behavior of the Correntina river basin.

Keywords: Hydrological modeling; Correntina River; Streamflow.

Calibração e validação do modelo SWAT para simulação hidrológica em uma bacia do Oeste da Bahia

A modelagem hidrológica se apresenta como uma ferramenta fundamental para gestão e gerenciamento dos recursos hídricos, visto que ela auxilia na compreensão do fluxo da água, sedimentos e contaminantes em uma bacia hidrográfica. A bacia do rio Correntina, localizada na região oeste da Bahia, vem sofrendo um intenso processo de alteração em sua paisagem motivado pela expansão das áreas agrícolas na região, sendo necessária a adoção de instrumentos para estudos que avaliem os impactos ambientais principalmente nos recursos hídricos superficiais. Visto isso, o presente trabalho teve como objetivo avaliar a eficácia do modelo SWAT para representação do comportamento hidrológico na bacia hidrográfica do rio Correntina, utilizando o SWAT-CUP para calibração e validação automáticas. Os coeficientes estatísticos de desempenho atestaram a capacidade do modelo para as simulações hidrológicas nessa bacia em escala temporal mensal, com KGE, Pbias, NSE e R^2 apresentando valores de 0.69, 0.57, 0.5% e 0.74 na etapa de calibração, e 0.73, -3.95%, 0.64 e 0.76 na etapa de validação, respectivamente. Além disso, o SWAT também se mostrou adequado para simulação das curvas de permanência, caracterizando o modelo como uma boa ferramenta de auxílio a gestão dos recursos hídricos na bacia em estudo. Estudos posteriores permitirão analisar os impactos do uso do solo e mudanças climáticas no comportamento hidrológico da bacia do rio Correntina.

Palavras-chave: Modelagem hidrológica; Rio Correntina; Vazão.

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INTRODUCTION

The western region of Bahia, in which the hydrographic basin of the Correntina river is inserted, underwent an intense process of economic transformation from the first half of the 1980s, due to the introduction of a modern and sophisticated agricultural system (SANTOS et al., 2018). Thus, the occupation of the rural area and the exploitation of natural resources, especially water resources, occurred (and still occur) in a disorderly and predatory manner, requiring that the government adopt measures to minimize environmental impacts through the efficient management of these resources (BAHIA, 1995).

To assist the management and preservation of water resources, understanding the hydrological behavior and analyzing the physical characteristics of a watershed is essential (BALBINOT et al., 2008). One of the scientific means for these studies and obtaining answers to the real effects of changes in the basin is through the modeling of environmental systems, which have aroused interest in the scientific community in general. This tool allows the representation of climatic, hydrological, hydraulic processes, water quality, environmental conditions, operational and economic aspects.

According to Ribeiro et al. (2017), modeling and geoprocessing are shown as a set of technologies of paramount importance for the study of river basins and sub-basins, and in this way, the government administration can find in this tool an important ally for the management of the water resources.

In the modeling of environmental systems, the use of hydrological models stands out, which allows the study and assessment of water balance on a spatial and temporal scale (TUCCI, 2005). These models have been gaining space by presenting themselves as an efficient instrument for assessing the hydrological behavior of watersheds, with Soil Water Assessment Tools (SWAT) being one of the most used and internationally known for showing itself as a robust interdisciplinary tool with regard to the modeling of hydrological processes (GASSMAN et al., 2007).

SWAT is a mathematical model in the public domain, with a semi-distributed and continuous parameter, which allows different physical processes to be simulated in the watershed (ARNOLD et al., 2012). According to Aragão et al. (2013), for predicting the impacts of human actions or climate change on hydrological processes, models with these characteristics have been quite effective.

Several studies used the SWAT in order to analyze the impacts of changes in land use and climate changes on the surface and underground runoff, sediment production, water quality, as well as pesticide transport. Santos et al. (2019), studying the effects of climate change in the Paraguaçu River basin using the SWAT model, demonstrated the reduction of surface flow in all climate change scenarios, relevant information to guide the future management of water resources in the region. Marmontel et al. (2019), evaluating the applicability of the SWAT model in the Paraibuna River basin, concluded that the model can serve as a tool for planning and managing public policies for water resources in river basins in the Atlantic Forest region. Dash et al. (2020) identified vulnerable areas under climate change scenarios in India with the SWAT model.

Given the above, taking into account the wide range of application of the SWAT model and its

potential as a tool to aid the management of water resources, in addition to the absence of such studies in the western region of Bahia, the present study aimed to evaluate the effectiveness of the SWAT model to represent the hydrological behavior in the Correntina River basin, whose area currently occupied by agriculture is 35%, and the region is facing, at the same time, an intense water crisis due to the reduction in the availability of surface water.

MATERIALS AND METHODS

Location and characterization of the study area

The Correntina River basin is located in the western region of the state of Bahia (Figure 1), occupying an area of 3852 km². It is one of the main tributaries of the São Francisco River. According to the Köppen (1931) classification, the climate in the region is classified as a Tropical sub-humid with summer rains (Aw), with a well-defined dry period in winter.

The course of the Correntina River is 220 km long, with its entire area inserted in the territory of the Correntina city. The region has typical Cerrado vegetation, with an area of natural vegetation divided between areas of savanna and rural formations, where the latter has extensive areas of dirty fields.

Figure 1: Location of the study area and climatic stations used.

Input database

For the use of the model, the following input data were needed: map of land use and occupation, type of soil, meteorological and rainfall conditions (precipitation, relative humidity, temperature, solar radiation and wind speed) and digital elevation model. According to Tucci (2005), the quantity and quality of data for calibration and validation of hydrological models are essential to allow satisfactory results.

The land use and occupation maps were obtained through the MapBiomass Project - Collection 4.1 of the 'Annual series of land use and coverage maps of Brazil'. The Project is a multi-institutional initiative that aims to generate annual maps of land cover and use from automatic classification processes applied to satellite images. Among the classes of land use and occupation in the Correntina River basin, agricultural

areas (AGRR) occupy 35% of the total area of the basin, followed by areas with savanna formation (RNGB), rural formation (RNGE), pasture (PAST), and forests (FRSD), with 31%, 26%, 4% and 4% of the study area, respectively.

The soil type maps were obtained from the open database of the Brazilian Agricultural Research Corporation (Embrapa). The predominant soils of the basin were the red-yellow Latosol, Neossolo Quartzarênico and Cambisol Háplico, occupying, respectively, 47.9%; 51.43% and 0.67% of the total area of the basin (Figure 2).

Precipitation data were acquired from the Hidroweb platforms of the National Water Agency (ANA) and Agritempo, while the other meteorological variables were acquired from the National Meteorological Institute (INMET). The solar radiation data were obtained through the grid of meteorological variables elaborated by Xavier et al. (2015). The monitoring of the basin under study is carried out by an ANA station (code 45590000), in the basin control section, located in the city of Correntina (Figure 1). To fill in the gaps present in the historical series of meteorological data, WXGEN was used, a model that generates the atmospheric state of the climate in the SWAT model, which simulates the series of climatic data or fills in gaps based on recorded data.

For this, some statistics from the historical series of observed data were calculated to feed the tool, such as TMPMX: Maximum temperature (°C); TMPMN: Minimum temperature (°C); TMPSTDMX: Standard deviation from the maximum temperature (°C); TMPSTD MN: Standard deviation of the minimum temperature (°C); PCPMM: Average precipitation (mm/day); PCPSTD: Standard deviation of daily precipitation (mm/day); PCPSKW: Slope coefficient for daily precipitation; PR_W1_: Probability of rainy day after dry day; PR_W2_: Probability of rainy day after rainy day; PCPD: Average number of rainy days (day); RAINHHMX: Maximum precipitation of 0.5 h (mm); SOLARAV: Average solar radiation (MJ/m²/d); DEWP: Average dew point temperature (°C); WNDV: Average wind speed (m/s); and RAIN_YRS: Number of years of data used to determine values for RAIN_HHMX (year). To obtain these statistics, the SWAT Weather Database was used, a tool developed by Essenfelder (2016) that calculates these parameters based on the inserted historical data series.

Figure 2: Maps of land use and soil types.

The Digital Elevation Model (DEM), with a spatial resolution of 30 m was acquired through the TOPODATA project, from the Shuttle Radar Topographic Mission (SRTM), whose data are made available by the United States Geological Survey (USGS).

Soil and Water Assessment Tools (SWAT)

Hydrological models seek a way to describe the behavior of a hydrographic basin, in addition to representing the portion of the hydrological cycle that transforms precipitation into the flow (TUCCI, 2005). For these analyzes it is necessary to use hydrological models with a physical and/or empirical basis, being SWAT (Soil and Water Assessment Tool) currently a prominent model worldwide.

SWAT was developed to analyze the hydrological dynamics, sediment and pesticide transport in watercourses. In addition, it also allows simulations to be carried out to assess the impacts of changes in land use and climate change in river basins (ARNOLD et al., 2012). In the SWAT model, the equation of the water balance continuity is used, integrating all models that estimate each component of the hydrological cycle, as described in Equation 1.

$$SW_t = SW_0 + \sum_{i=1}^t (R_{day} - Q_{surf} - E_a - W_{seep} - Q_{gw}) \quad (\text{Eq. 1})$$

Where SW_t is the final amount of water in the soil (mm), SW_0 is the initial soil moisture on the day i (mm), t is the time (days), R_{day} is the amount of precipitation on the day i (mm), Q_{surf} is the amount of runoff in the day i (mm), E_a is evapotranspiration on the day i (mm), W_{seep} is the amount of water that leaves the aeration zone of the soil profile on the day i (mm), Q_{gw} is the amount of flow return in the day i (mm).

SWAT has three models associated with the calculation of evapotranspiration for the simulation, namely Penman-Monteith, Hargreaves-Samani, and Priestley-Taylor, where the choice of the method to be used is associated with the climatic characteristics of the basin as well as the availability of data. In the present study, evapotranspiration was calculated using the Penman-Monteith method. The runoff was estimated using the SCS (Soil Conservation Service) curve number method, and the propagation in the channel was simulated by the variable storage method.

Calibration and Validation

The calibration of the SWAT model for the hydrographic basin of the Correntina river was performed automatically by the SWAT-CUP software, using the SUFI2 algorithm (Sequential Uncertainty Fitting). The simulation was performed on the monthly time scale, with a calibration period between January 1st of 2006 and December 31th of 2010, and validation between January 1st of 2011 and December 31th of 2015.

The basin under study was discretized into 21 sub-basins, later subdivided into 215 Hydrological Response Units (HRU), which allow the model to reflect the hydrological conditions for different slopes, cover and soil types on a small scale.

Ten parameters were used to be calibrated for the flow simulation, defined after conducting the sensitivity analysis. In the calibration process, the relative and replace methods were used. In SWAT there

are three methodologies to define the alteration of the parameters within the established limits, and through successive interactions, it is possible to know which parameters of the model are the most sensitive, being the replacement, absolute and relative methods. The replacement method changes the value directly, in absolute, a constant value is added to the initial value of the parameter and in the relative method, the change of values is established by varying the initial value by percentage.

Subsequently, the hydrographs were analyzed at each iteration and the parameters that affected peak flows had their intervals modified until the minimization of errors between the model outputs and the measured data. Finally, the validation step was performed with the parameters already adjusted after the calibration step. According to Medeiros et al. (2018), the validation aims to verify whether the model is capable of simulating data from other periods or conditions other than which it was calibrated.

Criteria for evaluating the model

To evaluate the performance of the model, four statistics were used: the Nash-Sutcliffe coefficient (NSE), the percentage of bias (Pbias), coefficient of determination (R^2) and the Kling-Gupta Efficiency (KGE). The NSE, whose calculation is based on Equation 2, indicates how much the graph of observed versus simulated data fits and varies from less infinite to 1, where 1 represents the perfect fit. This coefficient is indicated for long-term continuous simulations and can be used to determine how well the model simulates trends for the output response of interest (MORIASI et al., 2015).

$$NSE = \left[1 - \frac{\sum_{i=1}^n (Q_{o,i} - Q_{s,i})^2}{\sum_{i=1}^n (Q_{o,i} - Q_{o,m})^2} \right] \quad (\text{Eq. 2})$$

The percentage of bias is calculated according to Equation 3 and represents the deviation between observed and simulated data, expressed as a percentage. The Pbias value varies between less and more infinite, with zero as the optimal value, that is, the closer to 0, the better the model's performance. Negative and positive values indicate the overestimation or underestimation of the modeling, respectively.

$$Pbias = \left[\frac{\sum_{i=1}^n (Q_{o,i} - Q_{s,i})}{\sum_{i=1}^n Q_{o,i}} \right] \cdot 100 \quad (\text{Eq. 3})$$

The coefficient of determination (R^2) is widely used in hydrological modeling studies, and describes the degree of collinearity between simulated and observed data, and, according to Equation 4, varies between 0 and 1, with 1 being the optimal value.

$$R^2 = \left[\frac{\sum_{i=1}^n (Q_{o,i} - Q_{o,m})(Q_{s,i} - Q_{s,m})}{\sqrt{\sum_{i=1}^n (Q_{o,i} - Q_{o,m})^2} \sqrt{\sum_{i=1}^n (Q_{s,i} - Q_{s,m})^2}} \right]^2 \quad (\text{Eq. 4})$$

Gupta et al. (2009) developed an objective function called KGE (Kling-Gupta Efficiency) based on the decomposition of the Nash-Sutcliffe coefficient and the Mean Square Error (FRANCO et al., 2017). Like the Nash-Sutclif coefficient, KGE values range from $-\infty$ to 1, with 1 being the best fit.

$$KGE = 1 - \sqrt{(r - 1)^2 + (\beta - 1)^2 + (\alpha - 1)^2}, \alpha = \frac{\mu_s}{\mu_o}; \beta = \frac{\sigma_s}{\sigma_o} \quad (\text{Eq. 5})$$

In Equations 2, 3, 4 and 5, n is the number of observed and simulated pairs; Q_o is the observed flow,

Q_s is the simulated flow, $Q_{o,m}$ is the average observed flow and $Q_{s,m}$ is the simulated average flow. In Equation 5, r is the linear correlation coefficient; μ_o and μ_s are the arithmetic means of the observed and simulated values; σ_o and σ_s represent the standard deviation of observed and simulated values.

Table 1: Criteria for assessing the performance of the hydrological model and range of variation values.

Coefficient	Performance evaluation criteria				
	Very Good	Good	Satisfactory	Unsatisfactory	Range
R^2	$R^2 > 0.85$	$0.75 < R^2 \leq 0.85$	$0.60 < R^2 \leq 0.75$	$R^2 \leq 0.60$	-1 a 1
NSE	$NSE > 0.80$	$0.70 < NSE \leq 0.80$	$0.50 < NSE \leq 0.70$	$NSE \leq 0.50$	$-\infty$ a 1.0
PBIAS (%)	$PBIAS < \pm 5$	$\pm 5 \leq PBIAS < \pm 10$	$\pm 10 \leq PBIAS < \pm 15$	$PBIAS \geq \pm 15$	$-\infty$ a ∞
KGE	$KGE > 0.75$	$0.75 < KGE \leq 0.50$	$0.50 < KGE \leq 0.0$	$KGE \leq 0.0$	$-\infty$ a 1.0

Source: Moriasi et al. (2015) and Thieme et al. (2013).

RESULTS AND DISCUSSION

Table 2, shown below, lists the parameters indicated by the sensitivity analysis as those that most affect the model's output for the area under study. Because most parameters are difficult to estimate and measure in the field, their initial range of variation was adopted based on the values described in the analyzed literature, as suggested by Blainski et al. (2017).

Tabela 2: Parâmetros calibrados pelo modelo SWAT na simulação da vazão.

Ranking	Parameter	Description	Default	Calibrated values
1	r_CN2.mgt	SCS runoff curve number for moisture condition II	39-79	-0.71
2	v_RCHRG_DP.gw	Deep aquifer recharge (mm)	0.05	0.75
3	v_ESCO.hru	Soil evaporation compensation factor	0.95	0.98
4	v_GWQMN.gw	Threshold depth of water in the shallow aquifer for return flow to occur (mm)	1000	1951.5
5	v_REVAPMN.gw	Revaporation coefficient	750	13.0
6	r_SOL_AWC.sol	Available water capacity of the first soil layer (mm.mm-1)	0.05-0.3	0.09
7	v_GW_REVAP.gw	Coef. de ascensão da água à zona saturada	0.02	0.13
8	v_GW_DELAY.gw	Groundwater Delay (days)	31	497
9	r_SOL_K.sol	Saturated hydraulic conductivity of first soil layer (mm.h-1)	300-100	-0.1
10	v_ALPHA_BF.gw	Base runoff recession coefficient (days)	0.048	0.11

r _: relative method; v _: replacement method;

After conducting the sensitivity analysis, calibration and validation of the parameters, the SWAT model was considered able to simulate monthly flows in the Correntina River basin, since the statistical coefficients (Table 3) obtained on the monthly time scale attest to a good performance.

Table 3: Performance statistics of the SWAT model for calibration and validation on the monthly time scale.

Process	Period	Average streamflow (m ³ /s)		Estatísticas			
		Observed	Simulated	NSE	PBIAS	R ²	KGE
Calibration	2006-2010	27.88	28.01	0.57	0.5	0.74	0.69
Validation	2011-2015	27.61	26.52	0.64	-3.95	0.76	0.73

In the calibration step, the NSE was 0.57. According to the evaluation criteria developed by Moriasi et al. (2015) and described in Table 1, the model presented a performance considered “satisfactory” in the calibration stage. In the validation stage, the value of the Nash-Sutcliffe coefficient improved, with its value jumping to 0.64, and just as in the calibration stage, the model was considered “satisfactory”. Several authors used the SWAT model to simulate monthly flows, obtaining good values for statistical coefficients. Andrade

et al. (2013), performing the hydrological simulation in a watershed in the Alto Rio Grande-MG region, found values of the Nash-Sutcliffe coefficient of 0.66. Santos et al. (2018), calibrating the SWAT model in three sub-basins in the semi-arid region of Northeast Brazil, obtained the NSE coefficient for calibration and validation of 0.86 and 0.76, respectively, for monthly flows in the river sub-basin. Andaraí.

In the calibration and validation stage, the Pbias value was 0.5 and -3.95, respectively, a performance considered “very good”. Brighenti et al. (2016), using the SWAT model in a Santa Catarina watershed, found Pbias values of 0.1% and 2.6% during the calibration and validation stages, respectively, indicating slight underestimations of the model. Pereira et al. (2014), after carrying out the hydrological simulation using the SWAT in a watershed at the head of the coastal region of Brazil, obtained Pbias values of 0.70 and -4.8%, in the calibration and validation, in that order.

The values obtained from the R^2 statistic during the calibration and model validation stage were 0.74 and 0.76, respectively. Therefore, the model can be classified as “satisfactory” and “good”, in that order, according to Moriasi et al. (2015). Almeida et al. (2018), performing the SWAT calibration and validation for the Mucuri River watershed found the correlation coefficient for calibration with the value of 0.65 and 0.62 for validation. Silva et al. (2017) using the SWAT to estimate the flow in a hydrographic sub-basin of the Jequitinhonha River, obtained values of 0.62 and 0.75 for calibration and validation, respectively.

In the calibration step, the KGE was 0.69. According to the evaluation criteria described by Thiemeig et al. (2013), the model performed as “good” in the calibration stage. In the validation stage, the value of the Kling-Gupta efficiency coefficient improved, with its value jumping to 0.73, and as in the calibration stage, the model was considered “good”. Several authors have used this statistic to evaluate the efficiency of modeling jointly with PBIAS, NSE and R^2 . Franco et al. (2017), calibrating and validating the SWAT model for the Negro River basin, reached values of 0.67 for KGE in the calibration stage and 0.77 in the validation. Bisselink et al. (2016) obtained performance classified as intermediate of the calibrated model in a basin in Southwest Africa.

Through the evaluation and review criteria of available works, the results obtained in the calibration of the SWAT for the Correntina River basin are within the acceptable range for the model to be used in the hydrological simulation of the basin under study, according to the NSE statistical coefficients, Pbias, R^2 and KGE.

An important analysis of the performance of a hydrological model is realized by assessing the fit of the simulated and observed results using the hydrograph (Figure 2), making it possible to notice that in some periods of low flow the model underestimates the observed data. According to Aragão et al. (2013), this behavior is associated with the fact that the model is unable to reproduce the groundwater process well in this period because it is a significant component in the dry season, since in basins under aquifers, the surface flow is maintained by the underground reserves.

According to Blainski et al. (2017), a useful analysis to be performed after the calibration and validation stage is the ability of hydrological models to generate reliable data for the construction of the flow duration curve (Figure 3), which are essential tools in the preparation of river basin plans.

Regarding the maximum flow values, the model overestimated its values by 10%; however, the percentage of overestimation was within acceptable limits, as well as the underestimation of the minimum flow rates, which was 11%. There was an excellent adjustment of the average flow rates between 20 to 70% of permanence. Pereira et al. (2014) stated that errors of up to 30% in simulated flows are considered satisfactory for granting water grants in irrigated areas of Brazil. Thus, the SWAT model proved to be suitable for simulating flows on a monthly time scale in the Correntina River basin, making it possible to carry out studies on flood forecasting, analysis of changes in land use in the flow regime, water balance, and impacts of climate change on the hydrological behavior of the region.

Figure 2: Hydrograph of the simulated and observed flows and hietogram for the calibration (2006-2010) and validation (2011-2015) periods.

Figure 3: Observed and simulated flow duration curve.

CONCLUSIONS

The Correntina River basin proved to be suitable for the execution of the methods described in this study. According to the values obtained for the performance coefficients, the SWAT model is capable of satisfactorily simulating the monthly streamflow rates after the automatic calibration and validation steps. Subsequent studies will make it possible to analyze the impacts of land use and climate change on the hydrological behavior of the basin under study.

The analysis of the flow duration curve showed that the model can be used to assist in water management, presenting an overestimation of the highest flows resulting from extreme events, and underestimating the flows with minimal probabilities of exceedance, but within an acceptable range of error. Therefore, the present study attested to the applicability of the model as a management and planning tool for water resources in the Correntina River basin.

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